DEVELOPMENT OF A FUZZY PI CONTROLLER FOR A GRID CONNECTED WIND ENERGY CONVERSION SYSTEM

A Thesis Submitted in Partial Fulfilment of the Requirements for the

Award of the Degree of Master of Technology

in

Electrical Engineering

(Specialization: Control and Automation)

By:

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NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

PIN-769008, ODISHA

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To

My Parents

CERTIFICATE

This is to certify that the dissertation entitled "***Development of a Fuzzy PI Controller for a Grid Connected Wind Energy Conversion System***" being submitted by ***Shuchismita Acharya***, ***Roll No. 212EE3472***, in partial fulfillment of the requirements for the award of degree of ***Master Of Technology In Electrical Engineering (CONTROL AND AUTOMATION)*** to the ***National Institute of Technology***, ***Rourkela***, is a bonafide record of work carried out by him under my guidance and supervision.

(**Dr. Bidyadhar Subudhi)**
Professor
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Date:

Place:

DECLARATION

I hereby declare that the investigation carried out in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree/diploma at this or any other institution / University.

Shuchismita Acharya

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Shuchismita Acharya

ABSTRACT

In recent years power generation from renewable energy sources has gained importance in view of supplementing the power obtained from conventional sources. Out of all the renewable energy sources, wind energy conversion system is the greatest contributor to the power generations. During the recent years use of variable speed of the wind turbine is gaining much more importance than the fixed speed wind turbine. Important factors regarding variable speed operation are that it is easy to control and is even more efficient. Therefore, it is important to study the machine modelling of the double fed induction generator (DFIG) for a wind energy conversion system (WECS). One of the major areas in renewable power control includes the grid connected DFIG based WECS. Typically a DFIG based WECS consists of a Wind turbine connected to a DFIG and then the turbine-coupled DFIG is connected to the grid through a power electronic AC-AC converter.

In this thesis a grid connected wind energy conversion system using a simple PI controller is developed and then a fuzzy PI controller is designed to resolve the problem. Finally a comparison has been made to fuzzy controller from the simulation results, observing the efficiency of variation of DC link voltage variation.

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ABBREVIATIONS

DFIG	Double fed Induction Generator
PLL	Phase Locked Loop
GSC	Grid Side Converter
PI	Proportional Integral
MPPT	Maximum Power Point Tracking
FLC	Fuzzy Logic Controller
WECS	Wind Energy Conversion System
PWM	Pulse Width Modulation
LSC	Load Side Converter
M.I	Modulating Index

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

It is quite accepted that the earth's fossil energy resources are limited, and the cost of global oil, coal and gas production continues to rise beyond their peak. Fossil fuels belong to finite sources and so will be completely exhausted one day or the other. Comparing to the above case renewable energies have been in a great demand due to absence of the emissions of poisonous gases like carbon dioxide and sulphur dioxide. The various types of renewable energy sources contributing to current energy demand consist of water, wind, solar energy and biomass. However the major drawback suffered by hydroelectric power plants is its expensive and costly nature to build and also the plants must operate for a long time to become profitable. The creation of dams may even lead to flooding of lands leading to environmental destruction. Similarly solar energy can only be extracted from solar thermal collectors in the presence of sunlight. Due to this condition solar energy set up becomes impractical in areas where there is little sunlight or heavy rainfall. The reason behind the popularity of wind energy is due to its non polluting nature, greater efficiency and mainly due to its low operation cost. The increasing development of wind energy has resulted in many new modeling and improved simulation methods. Wind power harnessing procedure has been a task for many years. Since long back wind mills were put into the task of pumping water and grinding grain. Many new technologies such as pitch control and variable speed control methods have been tested and put forward since. Sometimes, wind turbine work in an isolating mode; therefore, there is no grid. Usually there are two, three or even more than three blades on a wind turbine. However according to aerodynamics concept, three blades is the optimum number of blades for a wind turbine. Asynchronous and synchronous ac machines are the main generators that are used in the wind turbines. A wind turbine extracts kinetic energy from the wind and converts this into mechanical energy. Finally, this mechanical energy is converted to electrical energy with the help of a generator. Therefore, the complete system that involves converting the energy of the wind to electricity is called wind energy conversion system. A wind turbine extracts the maximum amount of energy from the wind when operating at an optimal rotor speed, which again depends on speed of wind. The optimal rotor speed varies due to the variable nature of the wind speed. Research shows that variable speed operation of the rotor results in a higher energy production compared to a system operating at constant speed. A wind turbine model consists of blades, a generator, a power electronic converter, and power grid. Blades are used to extract power from the wind. By operating the blades at optimal tip speed ratio, maximum amount of energy can be extracted from the variable speed wind turbine. The maximum power point tracking (MPPT) control of variable speed operation is used to achieve high efficiency in wind power systems. The MPPT control is operated using the machine side control system. The function of pitch angle control scheme is to regulate the pitch angle by keeping the output power at rated value even when the wind speed experiences gusts. The double fed induction generator is associated with AC to AC converter, where generator is directly grid connected through the stator windings, keeping into account the grid voltage and frequency fixed. While the rotor windings are fed by rotor side converter at variable frequency through slip rings.

1.2 LITERATURE REVIEW

In the literature review section a detailed study of DFIG, of grid side vector control technique using traditional PI has been studied from “A doubly fed induction generator using back to back PWM converters and its application to variable speed wind energy generation”. Numerous researchers have done extensive work to make the dc link capacitor voltage constant regardless of any occurrence of grid faults. New techniques have been approached so as to make the performance of the grid side even better. Improved technique of fuzzy PI control was studied from “Decoupling Control of Doubly-Fed Induction Generator based on Fuzzy-PI Controller” .The extensive study regarding power or amount of energy available in the wind that can be converted to useful mechanical and then finally transforming into electrical form of energy has been shown. Ultimately, the successful study of the paper has shown the amount of energy that can be extracted to useful form of energy. Defining the terms such as tip speed ratio and also the betz coefficient has been carried out in the Papers [4]. The equation described in the paper shows that the term power coefficient is highly nonlinear because it changes with the change in the wind speed. The paper [3] represents a parabolic path stating the relationship between output power and wind speed. Various controlling techniques are applied to control the functions of the wind turbine [5]. The performance and modeling equations of a double fed induction generator have been governed by the nptel lectures and paper [2]. After studying through a various control techniques, finally a PI control method was implanted to make the dc link voltage constant. However, due to some limiting nature of the PI control a new improved technique was applied known as the fuzzy PI control technique.

1.3 MOTIVATION

- Wind power is the most reliable and quick developing among the various renewable energy sources. Wind turbines can operate both in fixed as well as variable speed operation mode.
- For a fixed speed operation the generator is directly connected to grid whereas for variable speed the generator is controlled with the help of power electronic equipments. Therefore double fed induction generator plays a vital role by operating in grid as well as in standalone mode.
- DFIG has attracted more attention due to its variable speed, reduced converter cost, less switching losses, higher energy efficiency and also for improved power quality. The controller in the double fed induction generator initially was implemented only with the help of a PI controller.
- However the problem associated with PI controller was the tuning of gains. Therefore PI controllers are difficult to control due to the tuning method. The problem was solved by changing the traditional PI controller with the improved Fuzzy PI controller.
- The advantage of using fuzzy control was to achieve a higher operation by the variation of the parameters. Fuzzy logic controller was superior over the conventional PI controller.

1.4 PROBLEM STATEMENT

Characteristics curve stating the relation of power, torque to rotor speed was coded for different wind velocities. Plotting was done in order to extract maximum amount of energy that could be converted to useful mechanical power. Implementing grid side using only PI controllers resulted in variation of the dc link voltage. Therefore a fuzzy PI controller was used instead of PI controllers to improve the dynamic response of the system.

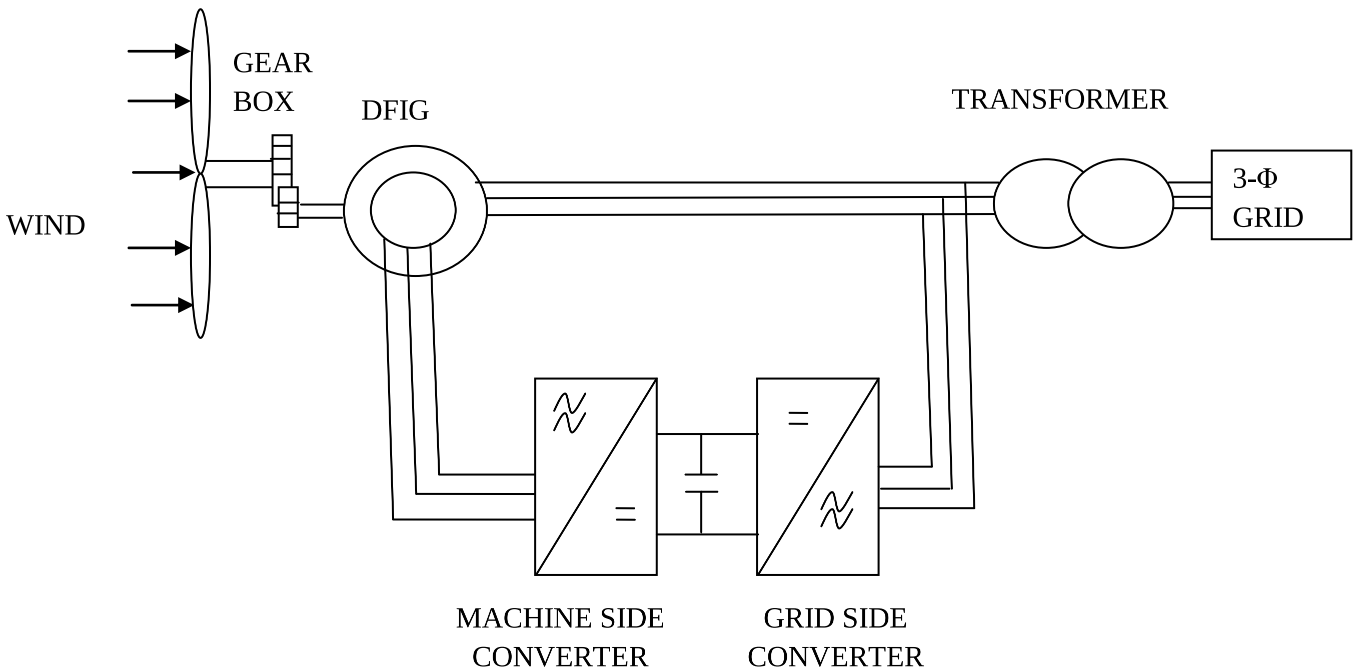


Figure 1.1: DFIG based wind energy conversion system

1.5 OBJECTIVE

i. To maintain the capacitor voltage constant and also the power factor should be maintained at unity.
ii. To generate a constant frequency from the variable speed operation of the shaft using the traditional PI.
iii. To design a Fuzzy PI controller for DC-link voltage control
iv. To implement the above controllers in MATLAB/SIMULINK

v. To compare the performances of a PI and fuzzy PI controller

1.6 THESIS LAYOUT

Chapter – 1: gives a basic idea as how wind energy has gained importance in the recent years and also the working principle of a wind turbine.

Chapter – 2: deals with the concept with the amount of power available and extracting maximum amount of energy from the wind. Conceptual idea regarding the characteristics of power and torque to rotor speed has been plotted.

Chapter – 3: covers the block diagram, equivalent circuit and modeling of double fed induction generator.

Chapter – 4: implements the grid side converter controller by maintaining the dc link voltage constant. Various control loops such as current control, voltage control and PLL control loop has been discussed. Results regarding the three phase grid voltage and constant dc link voltage have been simulated.

Chapter – 5: discussion of fuzzy PI implementation has been carried out. Rules regarding the input and output parameters for DC link voltage has been put forward to achieve better performance and stability condition. Comparison plot has been simulated showing that performance of fuzzy PI controllers is better than traditional PI controller.

Chapter – 6: gives the conclusions and scope of future work.

CHAPTER 2

MODELLING AND CONTROL OF WIND TURBINE SYSTEM

2.1 OBJECTIVE OF THE CHAPTER

To show the characteristics curve of power, torque and rotor speed for the variation of wind speed less than 12m/s and for the wind speed greater than 12m/s. Derivation of Betz coefficient is done, limiting the maximum capacity of power extraction. Control techniques of wind turbine system such as pitch and MPPT control have been described.

2.2 MODEL OF WIND SPEED

Wind power is basically in the form of kinetic energy moving above the earth's surface. Wind turbine blades collect the kinetic energy of air transforming into mechanical or electrical forms. The effectiveness of converting wind to other useful energy forms depend on the efficiency with which the rotor interacts with the wind flow.

Kinetic energy contained in wind is given by:-

$$E = \frac{1}{2} m v_{\circ}^{2} \tag{1}$$

Where m denotes the rate of flow of air and $v_{\circ}^{2}$ represents the speed of wind when undisturbed by anything.

Taking into account a wind rotor of cross sectional area A exposed to the wind flow, equation (1) is given by:-

$$E = \frac{1}{2} A V_{\circ} \rho v_{\circ}^{2} \tag{2}$$

Where $AV_{\circ}$ denotes the volume flow and $AV_{\circ}\rho$ represents the mass flow. $V_{\circ}$ is the volume of air accessible to the rotor. Hence power, can be expressed as

$$P_{\circ} = \frac{1}{2}\rho A v_{\circ}^{3} \tag{3}$$

From equation (3), we find that factors affecting the power available in the wind stream are the area of the wind turbine rotor, density, and the wind velocity. However the wind velocity effect is more due to its cubic relationship with the power.

2.3 MAXIMUM AMOUNT OF ENERGY TO BE EXTRACTED

Wind turbine cannot extract the power given in equation no. (3) completely from the wind. Only a section of its kinetic energy is transformed to the rotor, while the remaining air leaving the wind turbine is carried away. Therefore real power formed by a rotor will be decided according to the energy transferred that would take place from the wind speed to the rotor. This efficiency is defined as the power coefficient. Hence power coefficient of the rotor can be defined as the fraction of actual power developed by the rotor to the theoretical power available in the wind.

$$C_p = \frac{2P_{\circ}}{\rho A v_{\circ}^{3}} \tag{4}$$

Where $P_{\circ}$ is the power developed by the turbine.

The thrust force experienced by the rotor can be expressed as:-

$$F = \frac{1}{2}\rho A v_{\circ}^{2} \tag{5}$$

So rotor torque (T) can be expressed as follows:-

$$T = \frac{1}{2}\rho A v_{\circ}^{2} R \tag{6}$$

Where R is the rotor radius.

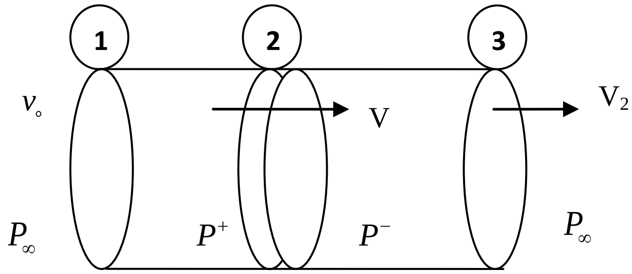


Figure 2.1: Power contained in wind

If surface (2) allows the air through it without any hindrance, then result is $v = v_\circ$ and $v_2 = v_\circ$ and therefore the power extracted is zero. If surface (2) allows a very large hindrance like wall, then all the $v_\circ$ is stopped near the surface (2) and so the power extracted is zero again. So in both the above cases we have zero power output. Hence we define a term known as axial interference factor (a). When a $=0$, it offers no interference and if a = 1, then there is complete blockage.

In-between there should be some value of (a), at which it should maximize. Therefore a is defined in terms of v and $v_\circ$ as:-

$$v = v_\circ(1-a) \qquad \left\{ \begin{array}{l} \text{If } a = 0, v = v_\circ \\ \text{If } a = 1, v = 0 \end{array} \right\} \tag{7}$$

Now obtain the expression of v_2 in terms of (a) and v_∞.

$$v_\circ(1-a) = \frac{1}{2}(v_\circ + v_2) \tag{8}$$

$$2v_\circ - v_\circ - 2v_\circ a = v_2 \tag{9}$$

$$v_2 = v_\circ(2-1-2a) \tag{10}$$

$$v_2 = v_\circ(1-2a) \tag{11}$$

Maximum amount of power extracted will be equal to drop in kinetic energy of the air.

So power extracted $(P_\circ) = \frac{1}{2}\rho A v(v_\circ^2 - v_2^2)$ (12)

Substituting v and v_2 in equation (12)

$$P_\circ = \frac{1}{2}\rho A v_\circ(1-a)[v_\circ^2 - v_\circ^2(1-2a)^2] \quad (13)$$

$$P_\circ = \frac{1}{2}\rho A v_\circ^3(1-a)[1-(1-2a)^2] \quad (14)$$

$$P_\circ = \frac{1}{2}\rho A v_\circ^3(1-a)[1-(1+4a^2-4a)] \quad (15)$$

$$P_\circ = \frac{1}{2}\rho A v_\circ^3[4a-8a^2+4a^3] \quad (16)$$

$$\frac{dP_\circ}{da} = 0 \quad (17)$$

$$\frac{dP_\circ}{da} = \frac{1}{2}\rho A v_\circ^3[4-16a+12a^2] \quad (18)$$

$$\frac{1}{2}\rho A v_\circ^3[4-16a+12a^2] = 0 \quad (19)$$

$$4-16a+12a^2 = 0 \quad (20)$$

$$a = 1, \frac{1}{3} \quad (21)$$

Therefore maximum power can be extracted when $a = \frac{1}{3}$

So $v = v_\circ(1-a)$ (22)

$$v = \frac{2}{3}v_\circ \quad (23)$$

Hence maximum power can be extracted only when speed goes to $\frac{2}{3}$ rd of $v_\circ$.

So substituting the value of $a = \frac{1}{3}$ in equation (16)

$$P_\circ = \frac{1}{2}\rho A v_\circ^3 [\frac{4}{3} - \frac{8}{9} + \frac{4}{27}] \tag{24}$$

Finally $P_\circ = (\frac{1}{2}\rho A v_\circ^3) \times (\frac{16}{27})$ (25)

Where $\frac{1}{2}\rho A v_\circ^3$ denotes the power contained in the wind and the value $\frac{16}{27}$ represents the maximum possible efficiency or the Betz coefficient.

The connection between the mechanical power and the wind speed passing through the turbine rotor can be given by the equation:-

$$P_m = (\frac{1}{2}\rho A v_\circ^3) \times C_p \tag{26}$$

$$P_m = (\frac{1}{2}\rho \pi R^2 v_\circ^3) \times C_p \tag{27}$$

Where P_m is the mechanical output power, $\frac{1}{2}\rho A v_\circ^3$ is the power contained in wind and C_p is the power coefficient of the wind turbine and is the function of the pitch angle, β and the tip speed ratio, λ.

2.4 TIP SPEED RATIO (λ)

The power delivered by a rotor at a definite wind speed depends on the relative velocity between the rotor tip and the wind speed. The fraction of the rotor blade tip speed and the unaffected wind velocity is expressed as tip speed ratio and is expressed as:-

TIP SPEED RATIO (λ) = $\frac{R\omega}{v_\circ} = \frac{2\pi R n}{v_\circ}$ (28)

Where n denotes the rotational speed in rotation per minute, R is the rotor radius, ω is the angular velocity and $v_{\circ}$ is the unaffected wind velocity.

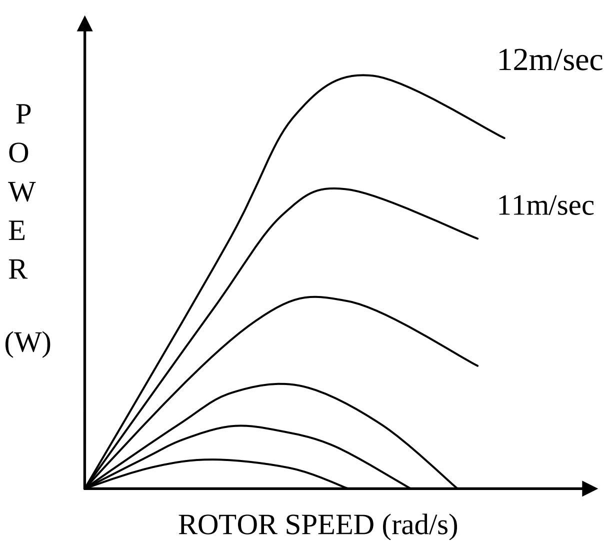
Value of $C_p(\beta, \lambda)$ is calculated as:-

$$C_p = 0.5176(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{\frac{-21}{\lambda_i}} + .0068\lambda \tag{29}$$

Where:-

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{30}$$

The Fig 2.2(a) describes that the power extracted by the turbine increases as the wind speed increases. Generated power reaches the rated power of the turbine, at the rated wind speed. But if the wind speed keeps on increasing, the output power also continues to rise and after a certain period of time the turbine has to be shut down when the speed exceeds a certain limit of the cut out wind speed. This is done for the safety purposes.



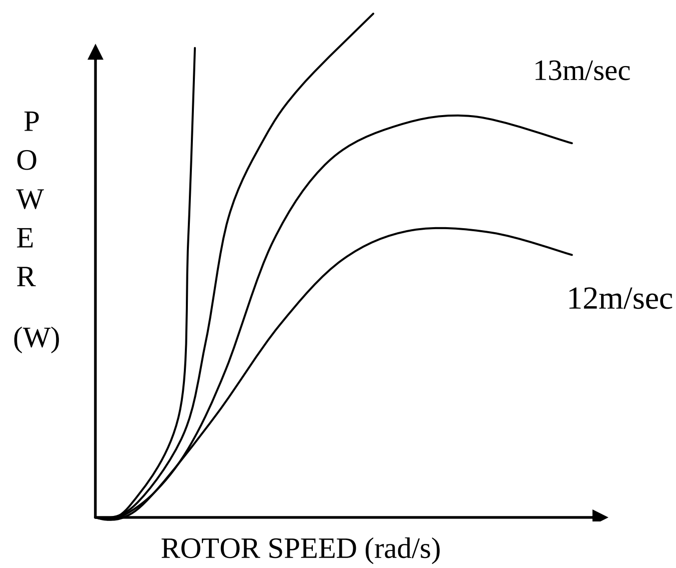


Figure 2.2: (a) Variation of wind (less than 12 m/s) (b) Variation of wind (greater than 12m/s)

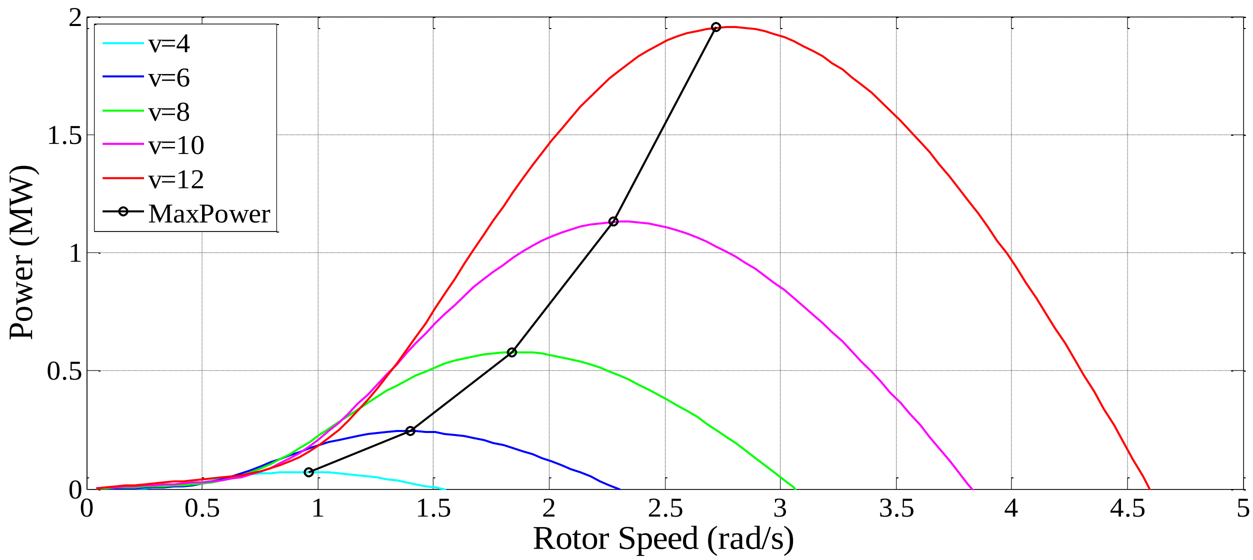


Figure 2.3: Characteristics curve of output Power and Rotor speed for wind speed less than 12m/s.

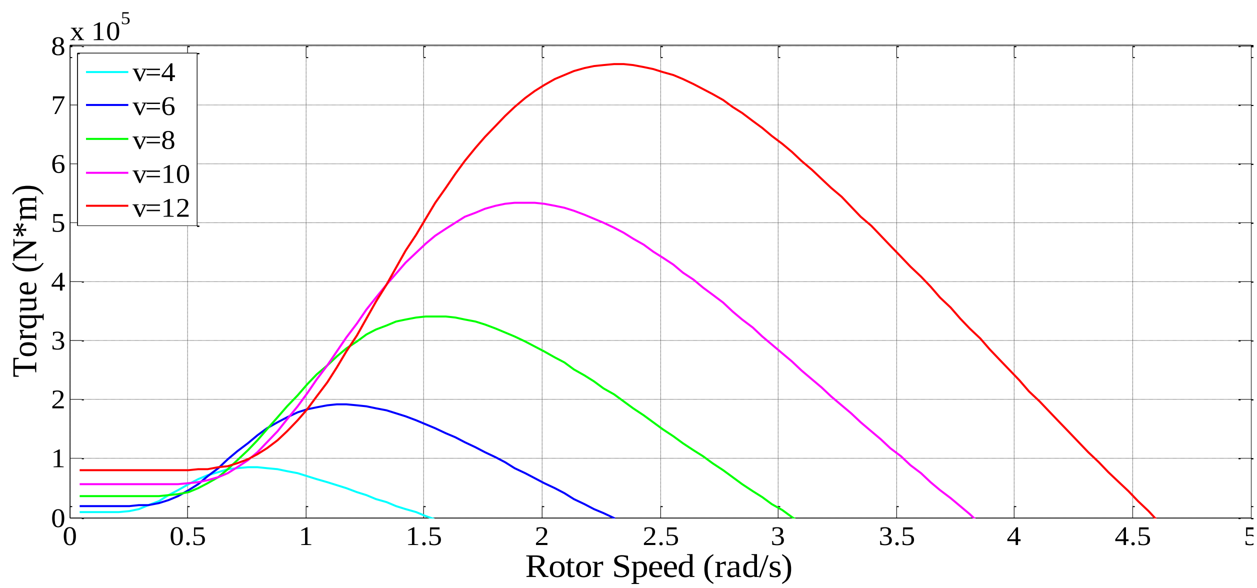


Figure 2.4: Characteristics curve of Torque and Rotor speed for wind speed less than 12m/s.

From the Fig. (2.3, 2.4) shows the characteristic curve between power and torque to rotor speed with different wind velocity from 4m/s to 12 m/s. When the velocity of wind is 4m/s, the maximum amount of power traced is approximately 0.9 m/s. When the velocity of wind goes on increasing, the availability of power also increases and so the maximum amount of power is obtained at wind velocity 12m/s. similarly with the increase in wind velocity the torque production also increases.

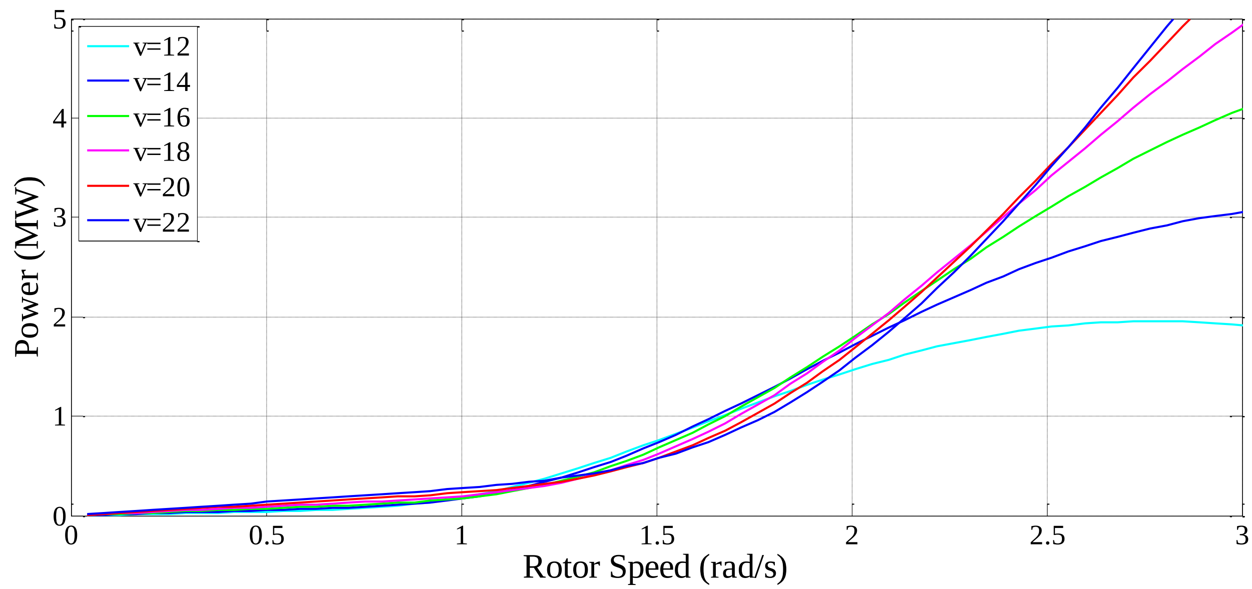


Figure 2.5: Characteristics curve of output Power and Rotor speed for wind speed greater than 12m/s.

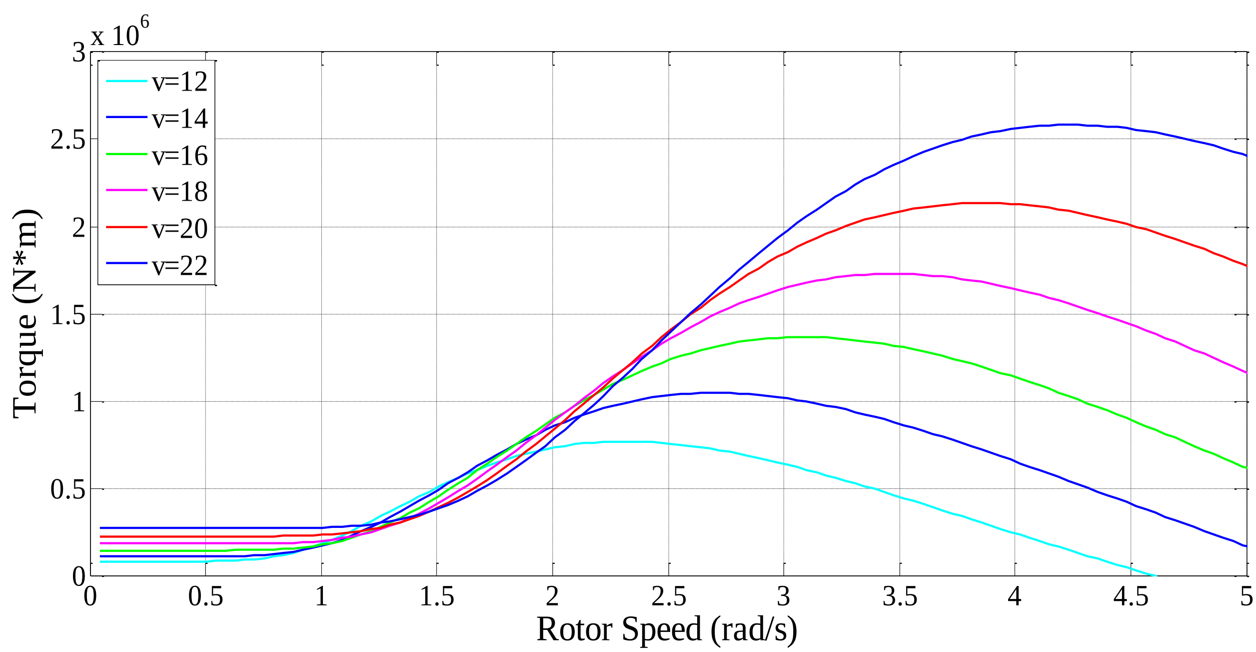


Figure 2.6: Characteristics curve of Torque and Rotor speed for wind speed greater than 12m/s.

Fig. (2.5, 2.6) shows that on increasing the wind velocity the power production also increases and also the torque production. When the velocity of wind is 22, maximum amount of torque production takes place.

2.5 POWER OUTPUT VERSUS WIND SPEED CHARACTERISTICS OF GENERATOR

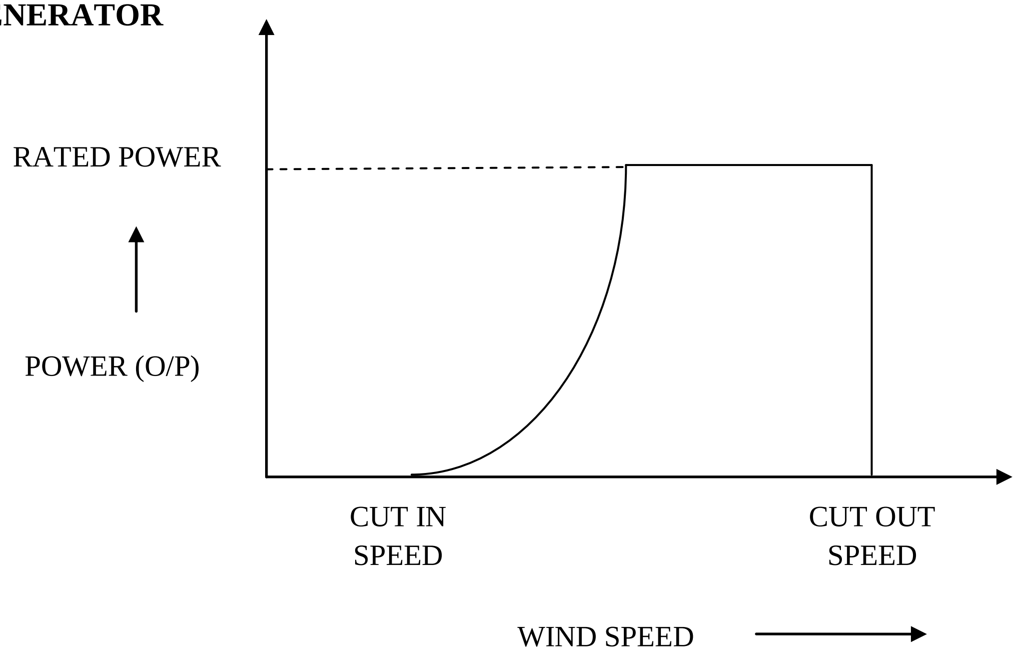


Figure 2.7: Power characteristics of wind turbine

At low wind speed power cannot be extracted. So the process of extraction starts from a specific point called as cut in wind speed. Below the cut in region, it might not rotate or in case if it is rotated no power can be extracted from it.

- Cut-in speed: cut in speed is the point at which wind speed is sufficient to extract the power. In this region the wind turbine starts to generate the power.

- Rated speed: in this region maximum amount of power extraction takes place. Over here the wind speed is in proportion to the amount of power contained in the wind. So the power contained in wind varies cubically with the wind speed. When the wind speed increases, there comes a particular state where the maximum amount of power extraction can take place and that is known as the rated power of the generator.

- Cut-out speed: most of the wind turbines are shut down in this region for safety purposes. This is done to protect the mechanical part of turbine from getting damaged.

2.6 CONTROL TECHNIQUES OF WIND TURBINE SYSTEMS

A controller continuously monitors and regulates the functions of the wind turbine. This is done in order to achieve the maximum amount of efficiency. The objective of the controller is to stop the turbine as soon as an error is generated.

2.6.1 Pitch Angle Control

This method is implemented to control the mechanical power input at the nominal value. Whenever the velocity of wind exceeds the rated value of power, a mechanical method is implemented so as to control the blade angle of the wind turbine from being damaged. At low wind speed, a control system technique is applied so that highest amount of power can be extracted from the wind. In this case, blades are turned back for the extraction of maximum amount of energy. While during the gusty wind condition the pitch angle is adjusted to limit the power extraction. This is done by turning the blades away from the wind. A pitch controller is used to regulate the blade angle by using proper simulation technique for capturing the wind energy. The conventional PI method was used before regarding the pitch angle control. However, advanced strategies such as fuzzy logic, generalized predictive control and self tuning regulator control are developing recently.

2.6.2 Maximum Power Point Tracking Control

Maximum power point scheme is used to extract highest amount of available energy from the wind, while it is operating over a large range of wind speed. According to maximum power point tracking the generator speed is adjusted according to the variations of wind speed. This is done so that the tip speed relation can be maintained at its optimal value λ_o. The conventional control schemes included the control mode of operation which used to depend on the setting of reference values. But in intelligent control technique, fuzzy logic control was used which has some advantages like speed control against wind gusts and having superior dynamic and steady state performances.

2.7 CHAPTER SUMMARY

Hence we draw the conclusion that the power extracted by the turbine increases with the amplification of the wind speed. At rated wind speed, the amount of generated power reaches the rated power of the turbine. But the output power greatly depends on the rate of the wind speed and continues to rise with the increase in the wind speed and after exceeding a certain limit; the turbine has to be shut down or else the gear box, the generator would be overloaded and they might burn. Description of Pitch angle and MPPT control states the regulation of wind turbine blades, according to the wind velocity.

CHAPTER 3

WIND TURBINE CONTROL FOR GRID CONNECTION

3.1 OBJECTIVE OF THE CHAPTER

Modelling of double fed induction generator is done to transform the actual variables into dq variables so that number of variables are reduced and is easy to simulate. A transformation matrix is obtained for the purpose and inverse transformation matrix is used to convert the dq variables back to the actual variables. Modelling of dc link capacitor is done to make the voltage constant irrespective of grid faults.

3.2 PERFORMANCE OF A DFIG

Doubly fed induction generator is a wound rotor induction generator, where the stator windings are directly linked to the grid while in the rotor side the windings are associated through slip rings to a three phase converter. Wound rotor is used in DFIG so that current could be fed from the rotor side as well as stator side. Operation of the DFIG can be done in standalone and also in grid connected mode. Rotor windings of an induction generator are connected to a power electronic converter, which can vary the voltage applied to the rotor windings. The major advantage of this scheme is a variable rotor speed is achieved, when connected to a constant grid frequency. Unbalanced grid connections, reduces the efficiency of the DFIG as the grid voltage is affected. This problem is tackled by DFIG as it can absorb as well as produce efficient quantity of reactive power from or to the grid so as to sustain the proper regulation of the voltage. Synchronous generators, is not directly related to the grid but connected through a medium of converter. In case of a grid connected system, the objective is to generate output voltage of constant frequency from a variable speed operation of the shaft. Although the rotational speed varies, the DFIG could still supply power at constant frequency as well as voltage. DFIG behaves superior to Synchronous generator as it allows the maximum power point tracking, higher efficiency of the turbine, capable to control at unity power factor and finally the improved amount of power quality achieved. Due to these reasons DFIG is gaining popularity for its variable speed among other generators of the wind energy conversion systems. If a DFIG is used as a generator, the cost of the converter is reduced and also there is a reduction in switching losses. Double fed induction generator is a wound rotor type induction machine, where the stator side circuit is linked to the grid directly, while in the rotor side; the windings are connected through slip rings to a three phase converter. Machine side converter is also known as rotor side converter and the converters are controlled separately irrespective of each other. The term 'doubly fed' has been derived because; voltage on the stator windings is applied from the grid while on the rotor windings voltage is induced by the power converter. So the rotor and stator both are linked to the electrical sources. The converter of double fed induction generator functions in a bidirectional power mode; either in sub-synchronous or in super-synchronous mode. In case of under synchronous operation active power is fed to the rotor from the supply. While active power is produced by the rotor and fed to the supply when operating over-synchronous speed. Among the two converters a dc link capacitor is placed, in order to keep the dc link constant and also to make the voltage variations ripple free.

3.3 DFIG MODEL

Fig.3.2 describes the equivalent star representation circuit of double fed induction generator, including magnetizing losses.

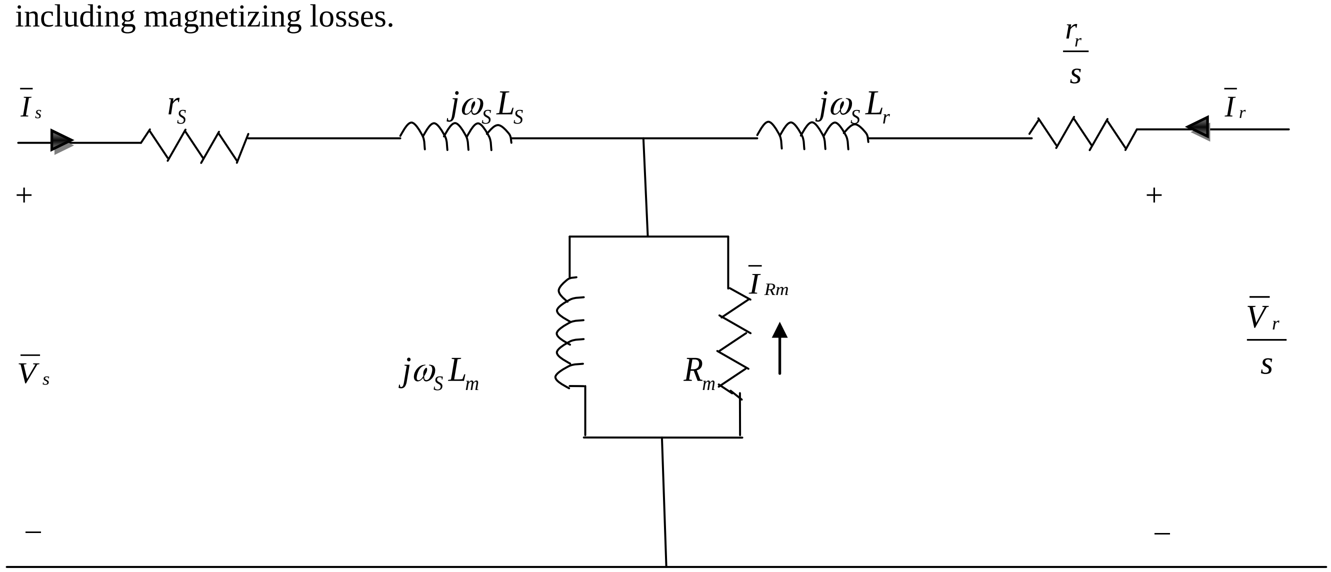


Figure 3.1: Circuit diagram of DFIG

The resistance and leakage reactance per phase of the stator windings are represented as r_S and $j\omega_S L_S$. While r_r and $j\omega_S L_r$ in the figure notify the resistance and leakage reactance per phase of the rotor winding on the rotor side. The DFIG circuit starts to operate as an ordinary squirrel cage induction type generator if in case the rotor voltage $\overline{V}_r$ is short circuited. Mutual reactance is given by $j\omega_S L_m$. When the rotor starts rotating at the angular velocity of ω_r rad/sec, the rotor resistance is transformed to $\frac{r_r}{s}$, where s is the slip and is given by $\left(1-\frac{\omega_r}{\omega_s}\right)$. The function of the rotor side converter is to induce three phase voltages at slip frequency.

The following expression is obtained by applying Kirchhoff's voltage law in the loop:-

$$\overline{V}_s = r_s \overline{I}_s + j\omega_S L_s \overline{I}_s + j\omega_S L_m (\overline{I}_s + \overline{I}_r + \overline{I}_{Rm}) \tag{31}$$

$$\frac{\overline{V}_r}{s} = \frac{r_r}{s} \overline{I}_r + j\omega_S L_r \overline{I}_r + j\omega_S L_m (\overline{I}_s + \overline{I}_r + \overline{I}_{Rm}) \tag{32}$$

$$0 = R_m \overline{I}_{Rm} + j\omega_S L_m (\overline{I}_s + \overline{I}_r + \overline{I}_{Rm}) \tag{33}$$

The flux regarding the air gap, stator and rotor are given by:-

$$\overline{\Psi_s} = L_S \overline{I}_s + L_m (\overline{I}_s + \overline{I}_r + \overline{I}_{Rm}) = L_S \overline{I}_s + \overline{\Psi_m} \tag{34}$$

$$\overline{\Psi_r} = L_r \overline{I}_r + L_m (\overline{I}_s + \overline{I}_r + \overline{I}_{Rm}) = L_r \overline{I}_r + \overline{\Psi_m} \tag{35}$$

3.4 DC LINK MODEL

In the grid side control, the amount of transformation of energy in the dc capacitor directly depends on the power delivered to the rotor circuit as well as power delivered to the grid.

$$\frac{d}{dt} E_{dc} = \frac{1}{2} C_{dc} \frac{d}{dt} V_{dc}^2 = -P_g - P_r \tag{36}$$

P_g is the amount of power delivered to the grid

P_r is the power delivered to the rotor circuit.

E_{dc} is the energy stored in the dc link capacitor.

V_{dc} is the dc link voltage

$$C_{dc}V_{dc}\frac{d}{dt}V_{dc} = -P_g - P_r \tag{37}$$

The condition to maintain the dc link voltage constant is:-

$$P_g = -P_r \tag{38}$$

3.5 MODELLING OF THREE PHASE SYMMETRICAL INDUCTION MACHINE

The three phase induction machine possesses three phases in stator and three phases in rotor. If the induction machine rotor is made up of squirrel cage, it means the rotor has symmetrical bars distributed over the surface of the rotor and shorted by means of end rings. Symmetrical bars have the advantage of being unaffected by any fault as the bar has same length and thickness throughout the length.

Modeling can be done in two different ways:-

1. Modeling in actual variables.

The actual variables over here are the voltages and current. Due to the presence of three current in stator we have three currents in rotor as well. The simulation is going to be complex if there are six variables, but if we transform these variables into dq model the complexity is greatly reduced with the reduction of the number of variables.

2. Modeling in dq variables.

Over here the three phase actual variables namely the abc (stationary) variables are transformed into two phase variables, that are the direct axes(d) and quadrature axes(q). The two axes, d and q axes are in a position of perpendicular to each other. The position of dq axes rotating at an angle ɵ are placed in an arbitrary position with respect to the stationary abc reference frame.

3.6 MODELLING IN ACTUAL VARIABLES

EQUATION OF STATOR

$$\underline{V}_{abcs} = \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = [r_s]\underline{i}_{abcs} + p\underline{\psi}_{abcs} \tag{39}$$

$[r_s]\underline{i}_{abcs}$ denotes the resistance drop and $p\underline{\psi}_{abcs}$ denotes the rate of change of flux linkages.

EQUATION OF ROTOR

$$\underline{V}_{abcr} = \begin{bmatrix} V_{ar} \\ V_{br} \\ V_{cr} \end{bmatrix} = [r_r]\underline{i}_{abcr} + p\underline{\psi}_{abcr} \tag{40}$$

Where stator and rotor currents are given by:-

$$\underline{i}_{abcs} = \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \quad , \quad \underline{i}_{abcr} = \begin{bmatrix} i_{ar} \\ i_{br} \\ ir \end{bmatrix} \tag{41}$$

3.7 TRANSFORMATION IN INDUCTION MACHINE

The objective is to transform the original machine into dq machine. This is done by assuming that number of turns in actual machine is same as that of the dq machine. The dq machine is a hypothetical machine, where the axis is stationary in the phase. There are two rotor windings, one in the d-axis, while the other in q- axis.

Equation of mmf in d-axis is given by:-

$$N_s i_{ds} = N_s \left(i_a + i_b \cos 120^o + i_c \cos 240^o\right) \tag{42}$$

$N_s i_{ds}$ is the d axis mmf produced by the dq winding in stator.

The mmf produced by d axis stator will be same as the mmf produced by the abc stator in d axis. So by projecting the phase b, phase c and phase a mmf all along the d axis, which is aligned along the phase a of the stator, we equalize the mmf of the dq machine and the abc machine in the stator.

$$N_s i_{ds} = N_s \left(i_a - \frac{1}{2} i_b - \frac{1}{2} i_c \right) \tag{43}$$

The stator currents are given by

$$i_{ds} = \left(i_{as} - \frac{1}{2} i_{bs} - \frac{1}{2} i_{cs} \right) \tag{44}$$

Similarly we equalize the mmf in q-axis by

$$N_s i_{qs} = N_s \left(i_{bs} \frac{\sqrt{3}}{2} - i_{cs} \frac{\sqrt{3}}{2} \right) \tag{45}$$

$$i_{qs} = \left(i_{bs} \frac{\sqrt{3}}{2} - i_{cs} \frac{\sqrt{3}}{2} \right) \tag{46}$$

Therefore finally the transformation of the current is done from the actual variables to the dq variables. In additional to the dq component, zero sequence components do also exist. The equation of the zero sequence component is given in equation no (47).

$$i_{os} = \frac{1}{3}\left(i_{as} + i_{bs} + i_{cs} \right) \tag{47}$$

The major important part is that while transforming from the actual variable the per phase are kept exactly the same as the per phase of the dq machine

The matrix form is represented as follows:-

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{os} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{48}$$

The transformation matrix is represented as $[C_s]$ and is given by

$$[C_s] = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (49)$$

The same transformation is applied for the current, voltage and flux linkage. Voltage, current and flux linkage are all vectors and so the transformation matrix is used to convert them to dq machine. Therefore the transformed equations are:-

$$\underline{i}_{dqos} = C_s \underline{i}_{abcs}$$
$$\underline{V}_{dqos} = C_s \underline{V}_{abcs}$$
$$\underline{\psi}_{dqos} = C_s \underline{\psi}_{abcs}$$

3.8 ROTOR TRANSFORMATION

Rotor transformation involves rotor angle and is transformed to a two axis model. This is done by projecting the mmf in the d and q axis respectively and then finding out the dq current for the rotor in a similar way done for the stator.

$$N_r i_{dr} = KN_r \left(i_{ar} \cos\theta_r + i_{br} \cos(\theta_r + \frac{2\pi}{3}) + i_{cr} \cos(\theta_r - \frac{2\pi}{3}) \right) \quad (50)$$

Over here the mmf in d axis is equalized.

Similar conditions are applied in case of q axis also. However the single variation that is done is by changing the cos component to sine.

$$N_r i_{qr} = KN_r \left(i_{ar} \sin\theta_r + i_{br} \sin(\theta_r + \frac{2\pi}{3}) + i_{cr} \sin(\theta_r - \frac{2\pi}{3}) \right) \quad (51)$$

Further the zero sequence component is given by:-

$$i_{or} = \frac{1}{3}(i_{ar} + i_{br} + i_{cr}) \tag{52}$$

Finally the rotor transformation to rotor current is given by the matrix:-

$$\begin{bmatrix} i_{dr} \\ i_{qr} \\ i_{or} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \sin\theta_r & \sin(\theta_r + \frac{2\pi}{3}) & \sin(\theta_r - \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix} \tag{53}$$

Now as the transformation for the stator and transformation of the rotor are known. Therefore the actual variables (abc) can be transformed into dq variables. The same transformation can be applied for current, voltage and also the flux linkage.

3.9 TRANSFORMATION OF ABC EQUATIONS INTO DQ EQUATIONS

STATOR EQUATIONS

$$\underline{V}_{abcs} = [r_s]\underline{i}_{abcs} + p\underline{\psi}_{abcs} \tag{54}$$

Premultiplying the above equation with C_s

$$C_s\underline{V}_{abcs} = C_s[r_s]C_s^{-1}C_s\underline{i}_{abcs} + C_s p\underline{\psi}_{abcs} \tag{55}$$

$$\underline{V}_{dqos} = C_s[r_s]C_s^{-1}C_s\underline{i}_{dqos} + C_s p\underline{\psi}_{abcs} \tag{56}$$

Expanding the equation we get:-

$$\underline{\psi}_{abcs} = [L_{ss}]\underline{i}_{abcs} + [L_{sr}^1]\underline{i}_{abcr}^1 \tag{57}$$

The equation consists of flux linkage due to self inductance and flux linkage due to mutual inductance between stator and rotor.

The term $[L_{sr}^1]\underline{i}_{abcr}^1$ is referred from primary side by multiplying with suitable number of turns.

The equation (57) is transformed by pre multiplying with C_s .

$$C_s \underline{\psi}_{abcs} = C_s \left[L_{ss} \right] C_s^{-1} C_s \underline{i}_{abcs} + C_s \left[L_{sr}^1 \right] C_r^{-1} C_r \underline{i}_{abcr}^1 \tag{58}$$

This equation helps to transform the inductances of the abc machine into the inductances of the dq machine.

The variable $C_s \left[L_{ss} \right] C_s^{-1}$ represents the stator self inductance independent of θ_r . Therefore if we transform this variable into the dq model it still remains independent of θ_r except the additional of some new factors.

$$C_s \left[L_{ss} \right] C_s^{-1} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} L_{Ls} + L_{ms} & -\frac{1}{2} L_{ms} & -\frac{1}{2} L_{ms} \\ -\frac{1}{2} L_{ms} & L_{Ls} + L_{ms} & -\frac{1}{2} L_{ms} \\ -\frac{1}{2} L_{ms} & -\frac{1}{2} L_{ms} & L_{Ls} + L_{ms} \end{bmatrix} \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \tag{59}$$

L_{ms} denotes the mutual inductance between the two-phase of stator.

After simplifying the inductance matrix of dq machine is obtained, in which the diagonal elements are only present, off diagonal elements are zero because there is no coupling between the d and q axis. The d and q axis are orthogonal to each other and they are perfectly decoupled.

$$C_s \left[L_{ss} \right] C_s^{-1} = \begin{bmatrix} L_{Ls} + \frac{3}{2} L_{ms} & 0 & 0 \\ 0 & L_{Ls} + \frac{3}{2} L_{ms} & 0 \\ 0 & 0 & L_{Ls} \end{bmatrix} \tag{60}$$

3.10 MODEL OF INDUCTION MACHINE IN STATIONARY REFERENCE FRAME EQUATIONS FOR STATOR

Since stator is stationary, hence the stator does not have any rotationally induced emf and the flux linkage can therefore be expressed in terms of inductance and current.

$$V_{ds} = r_s i_{ds} + p\psi_{ds} = r_s i_{ds} + L_s p i_{ds} + L_m p i^1_{dr} \qquad (61)$$

$$V_{qs} = r_s i_{qs} + p\psi_{qs} = r_s i_{qs} + L_s p i_{qs} + L_m p i^1_{qr} \qquad (62)$$

Where i^1_{dr} is the current referred from primary side.

Over here the zero sequence component is not considered because the zero sequence equation does not take part in torque production.

Similarly the equations for d and q axis voltage of the rotor are given by:-

$$V^1_{dr} = r^1_r i^1_{dr} + p\psi^1_{dr} + \omega_r \psi^1_{qr} \qquad (63)$$

$$V^1_{qr} = r^1_r i^1_{qr} + p\psi^1_{qr} - \omega_r \psi^1_{dr} \qquad (64)$$

Where V^1_{qr} and V^1_{dr} represents the q-axis and d axis voltage and $\omega_r \psi^1_{qr}$ represents the rotationally induced emf which is a function of speed of the rotor.

Rotor possesses the rotationally induced emf and also is a function of speed.

By expressing the equations (63) and (64) in terms of current are given by:-

$$r^1_r i^1_{dr} + L^1_r p i^1_{dr} + L_m p i_{ds} + \omega_r (L^1_r i^1_{qr} + L_m i_{qs}) \qquad (65)$$

$$r^1_r i^1_{qr} + L^1_r p i^1_{qr} + L_m p i_{qs} - \omega_r (L^1_r i^1_{dr} + L_m i_{ds}) \qquad (66)$$

So the above equations are implemented and are helpful for finding the necessary amount of torque required for the induction machine.

The Fig (3.4, 3.5) represent the equivalent circuit of double fed induction machine in the dq reference frame. In the figure $s\omega_s$ denotes the divergence between the synchronous speed and rotor speed. The mutual inductance is represented by L_m . The subscripts r, s, d and q represent the rotor, stator, d-axis and q-axis.

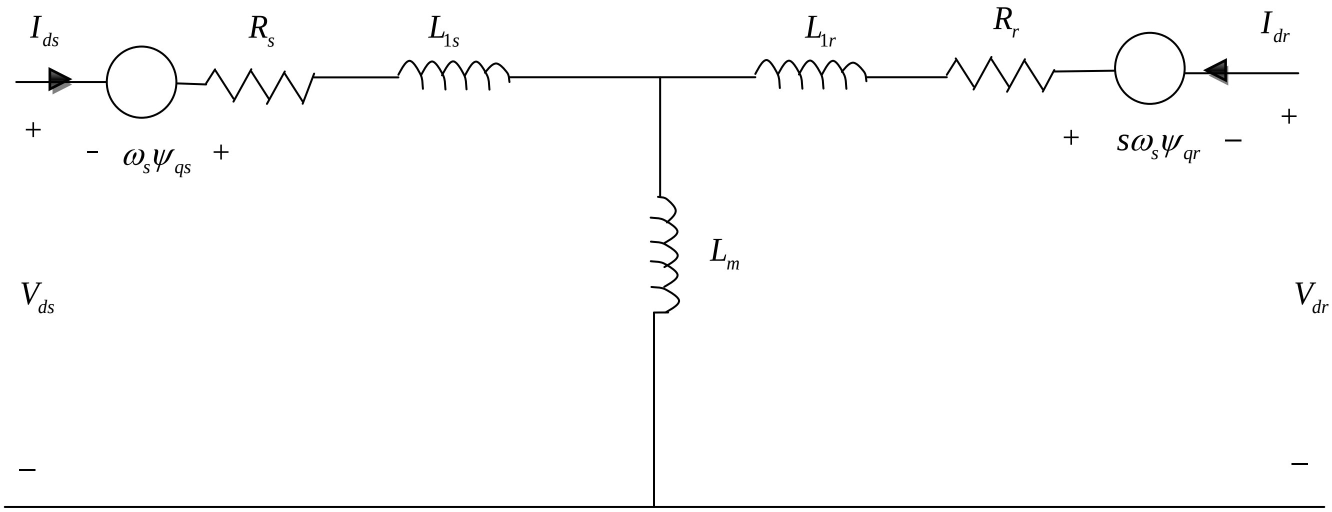


Figure 3.2: Model of d – axis

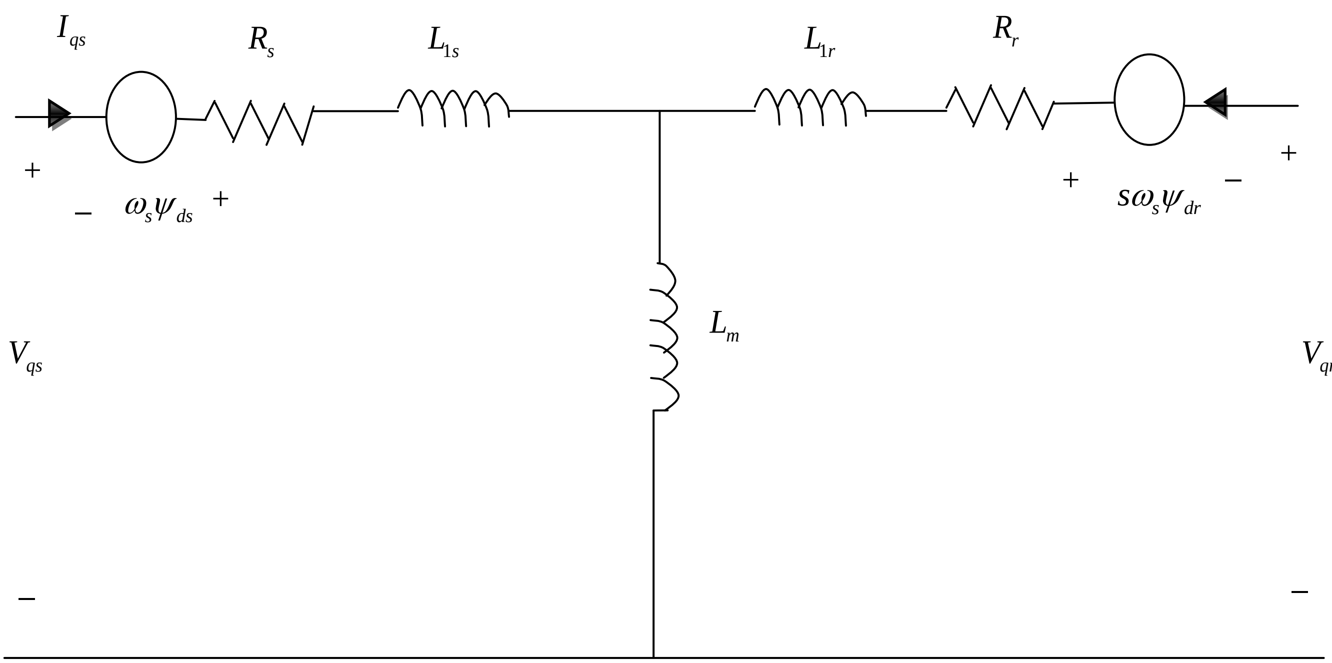


Figure 3.3: Model of q – axis

3.11 CHAPTER SUMMARY

Transformation from abc to dq and vice versa has been done with respect to the reference frame. A transformation matrix has been obtained to make the conversion successful. Finally from the equivalent circuit diagram two separate models of d and q axis have been obtained. Operation of the wind speed turbine with double fed induction machine has been studied. Modelling of the dc link capacitor was done so as to make the voltage ripple free from regarding any grid faults.

CHAPTER 4

CONVERTER CONTROL RECTIFIER

4.1 OBJECTIVE OF THE CHAPTER

Control of supply side using simple PI controller was achieved to make the dc link voltage constant. Voltage balance equations are derived with respect to reference frame rotating at ω_e Current control and voltage control loops are designed using the PI controllers only. A three phase PLL technique was implemented to measure the phase angle.

4.2 LOAD SIDE CONVERTER (LSC) CONTROL

The purpose behind the load side converter is to maintain the power factor at unity by controlling the reactive power flow injected into the grid and also to maintain the capacitor voltage constant such that it is independent of the direction of rotor power flow. Connection of a capacitor on the dc link provides a dc voltage source. Control scheme for the load side converter follows the decoupling of dq axis using the vector control methods. The dc link voltage has to be controlled independently of the direction of the slip power and to maintain a constant value; balance of power is of equal importance between the rotor and the grid side. The vector control method is implemented in the grid side by decoupling the dq axis currents for controlling and maintaining the dc link voltage to be constant. The rate or amount of power flow is finally decided by the load. Power flow is adjusted using the phase shift angle among the difference of the input voltage and source voltage. Decoupled controls of active and reactive power flowing between rotor and grid are performed by using voltage vector control. Over here the function of d axis current is to control and maintain the dc voltage constant, whereas work of the q axis current is used to keep the desired value of reactive power flow between the grid side and the point of common coupling. The function of the vector control method is to control the active as well as reactive power separately. During super synchronous operation mode, the real power of doubly fed induction generator flows to the rotor side converter from the windings of the rotor and also to the load side converter and to the supply grid through the dc link. Therefore the converter at the load side starts to operate as an inverter. Now considering the case of sub synchronous operation mode the converter at the grid side behaves as a rectifier and the direction of the real power flow is through the converter at the grid side, dc link and then finally into the rotor side converter. The process of the converter at the grid side can be controlled by using a loop within a loop concept, i.e.; by cascading a current control loop inside the dc link voltage control loop. Fig 4.1 [1] represents the load side converter control.

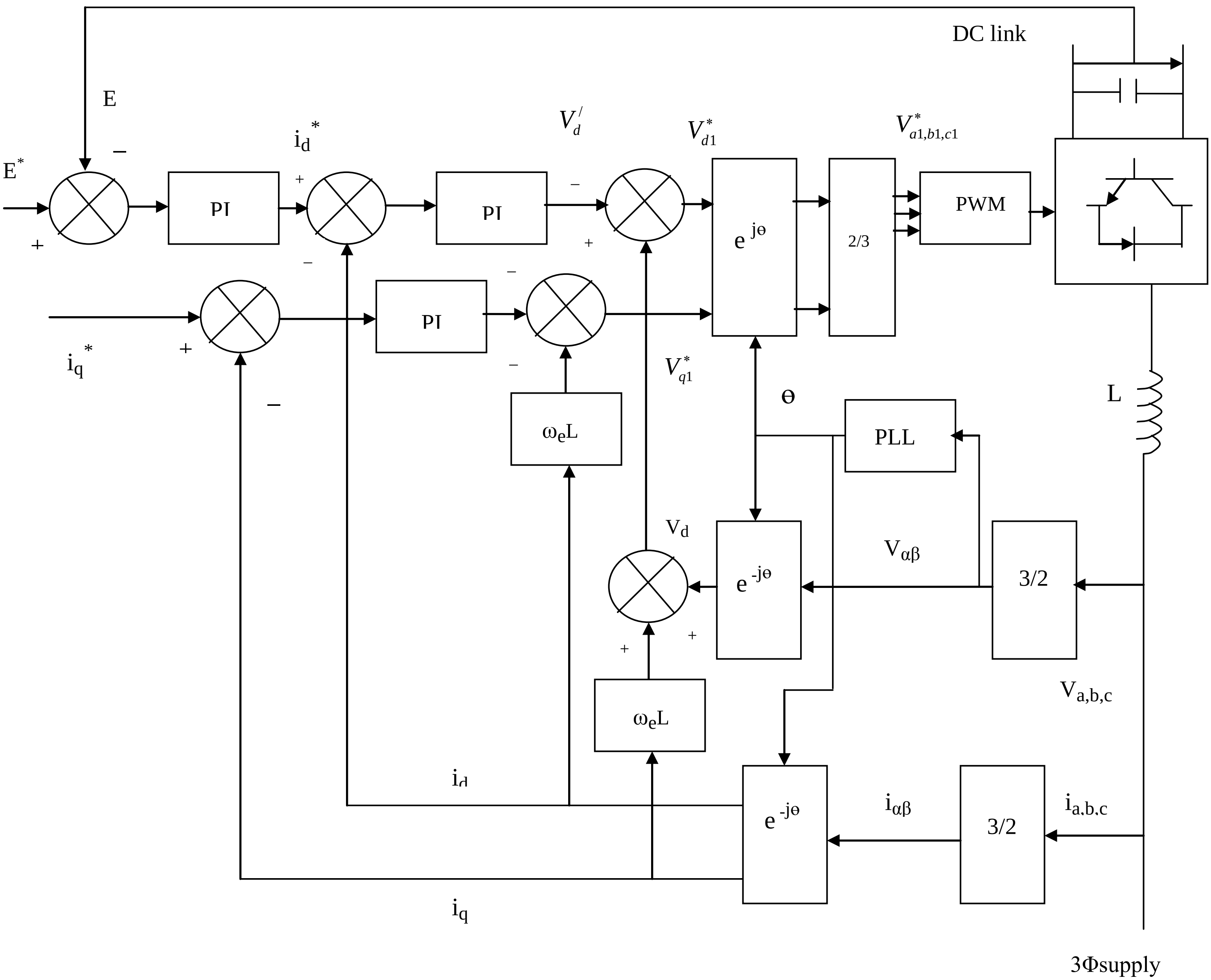


Figure 4.1: Grid side converter structure

Voltage stability equation across the inductors is given by:-

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} \tag{67}$$

Where L and R represents the line inductance and resistance, respectively.

By using the transformation and converting the equation (67) into dq reference frame rotating at ω_e , the new transformed equation is given by:-

$$V_d = Ri_d + L\frac{di_d}{dt} - \omega_e L i_q + V_{d1} \tag{68}$$

$$V_q = Ri_q + L\frac{di_q}{dt} + \omega_e L i_d + V_{q1} \tag{69}$$

The Fig. 4.2 [1] shows the supply side converter arrangement.

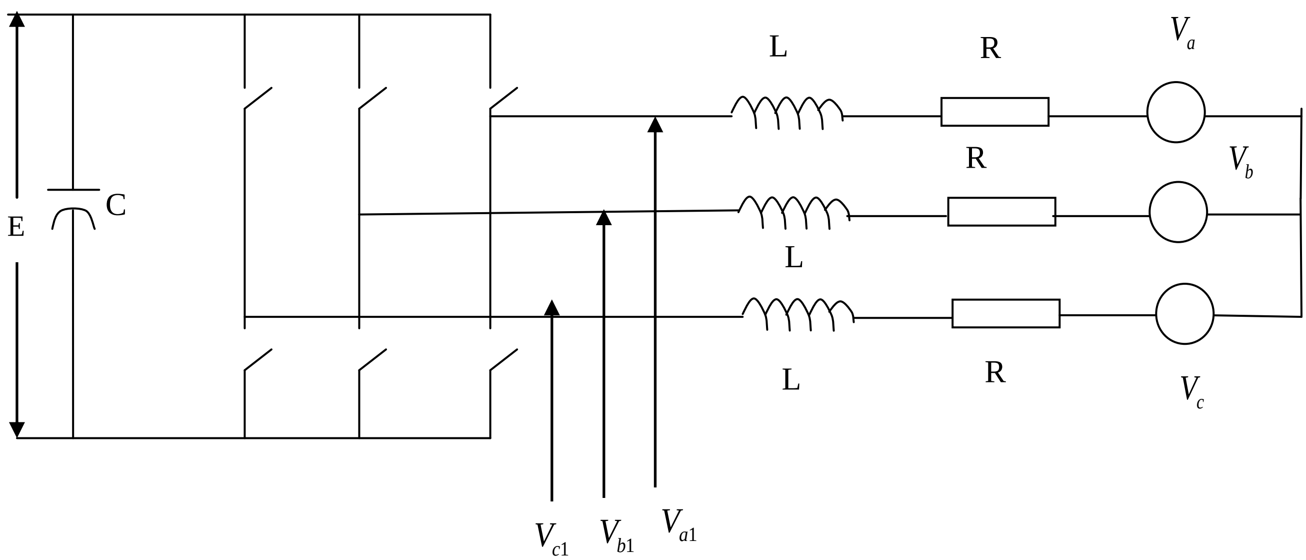


Figure 4.2: Schematic diagram of Converter

V_{a1}, V_{b1}, V_{c1} = Three Phase Stator Converter terminal Voltages; E = DC link voltage

Objective over here is to keep the voltage E constant, although a three phase ac supply is given to the converter. The converter operates as a six switch and a pulse is generated, when the reference signal is compared with the triangular signal. The reference signal is a sinusoidal signal.

4.3 CURRENT CONTROLLERS

PI controller is tuned for only one current controller and is then fed to the inverter, assuming the value of the other current controller loop to possess the same value. This is done by using a demultiplexer. The main objective of the PI controllers is to obtain the dq- axis voltages by using the reference current values from the current control loop. Over here the converter is delayed by two sample periods. The PI converter is cascaded with the inverter, and further the inverter is cascaded to the plant. Fig. 4.3 represents the block diagram of the current control loop system.

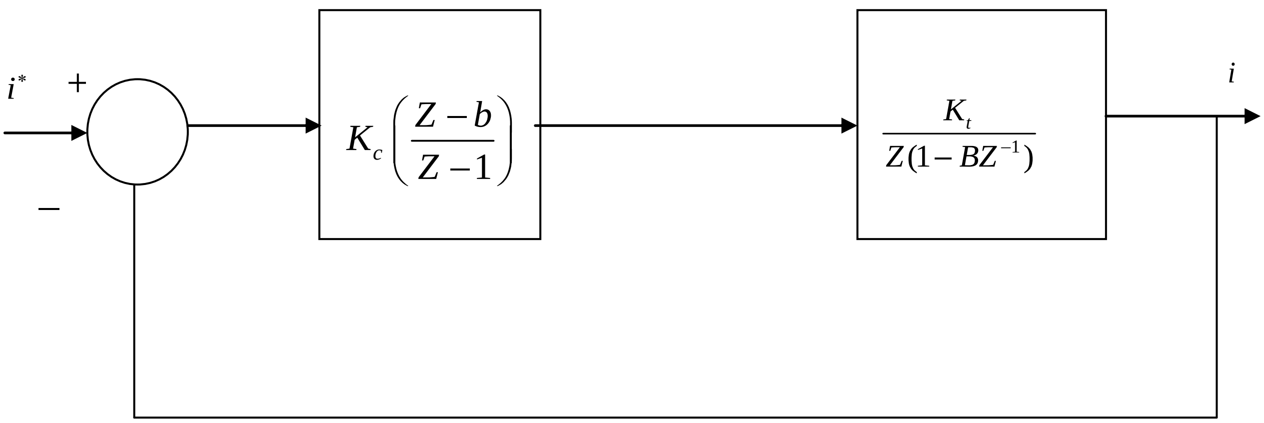


Figure 4.3: Current Control Loop

The transfer function of the plant in continuous domain is given by

$$F(s)=\frac{1}{LS+R} \tag{70}$$

By converting the continuous domain transfer function into discrete domain equation (70) becomes $F(Z)=\frac{(1-B)}{R(Z-B)}$ where $B=e^{-(R/L)T_s}$ (71)

R and L represent the line resistance and inductance. T_s is the sampling time and for the current control loop it is given by 0.5 ms and PI controller transfer function is given by:-

$$G(z) = 4.72\frac{(Z-0.96)}{(Z-1)}. \tag{72}$$

4.4 DC VOLTAGE CONTROLLERS

The actual goal of the dc voltage controllers is to maintain the capacitor voltage constant under the normal condition as well as during grid faults conditions also. Depending upon the balance condition of the power exchanged by the converter, the dc link voltage control is also changed. Current loop is an inner loop, while the dc voltage control loop belongs to the outer loop. Fig.(4.4) shows the basic voltage control loop diagram.

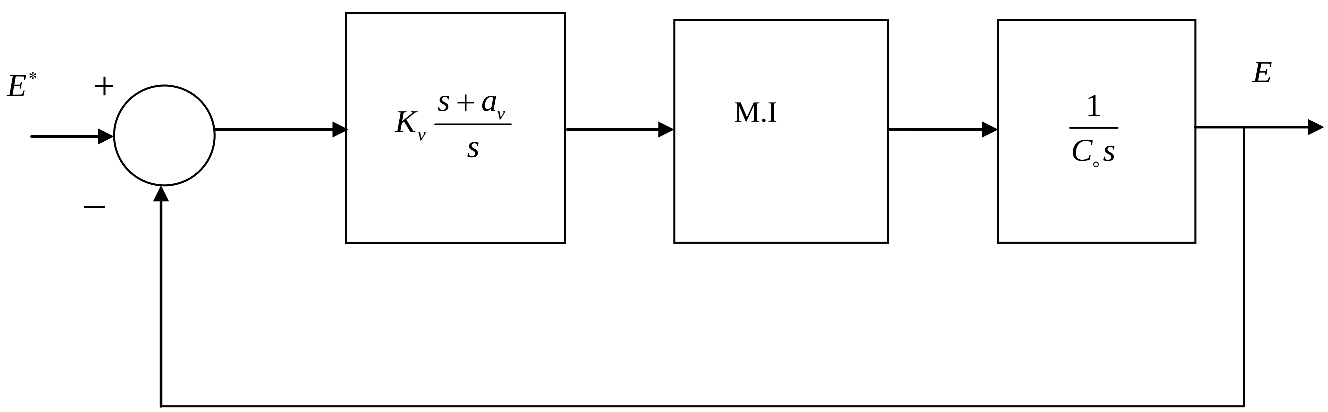


Figure 4.4: Voltage Control Loop

E* = Reference Voltage, E = Voltage, C_o = DC capacitance

The dc-link voltage is maintained at 550V and the capacitive value being 2.4mF. The value of stator converter modulation depths (m_1) is rated at 0.70. Sampling time of the dc link voltage control loop is 5ms. The PI controller transfer function is given by

$$0.12\frac{(Z-0.9248)}{(Z-1)} \tag{73}$$

Table 4.1: Grid Side Converter Gains

Controllers	Current Control	Voltage Control
Proportional Gain(K_p)	4.5312	0.110976
Integral Gain(K_i)	0.012	0.0614

4.5 PHASE LOCKED LOOP (PLL)

Phase locked loop has a wide area of application like in radio, computers and electric motor control. One of the major advantages of using phase locked loop lies in that it can be used for a wide area of frequency range starting from a few hertz to orders of gigahertz. PLL is used to determine the grid frequency and the phase angle. PLL is essentially divided into two major parts. Firstly the phase detection part and secondly the loop filter. The inputs to the PLL block consist of three phase sinusoidal signals. The three phase voltages of the grid are converted to dq module and are then fed to the PLL controller. The function of the PLL controller mainly lies in the detection and reduction of the error to a minimal value. Phase locking of PLL is considered only when the controlling voltage of the d-axis becomes zero. The basic diagram of PLL control loop is shown in Fig (4.5).

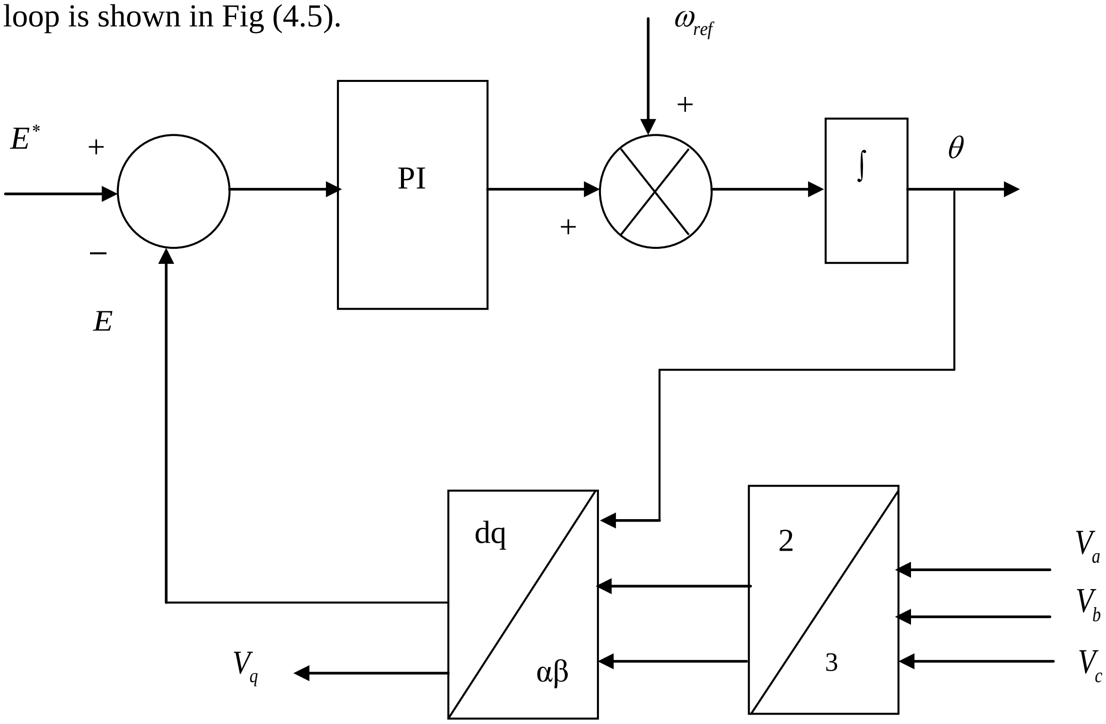


Figure 4.5: PLL Control Loop

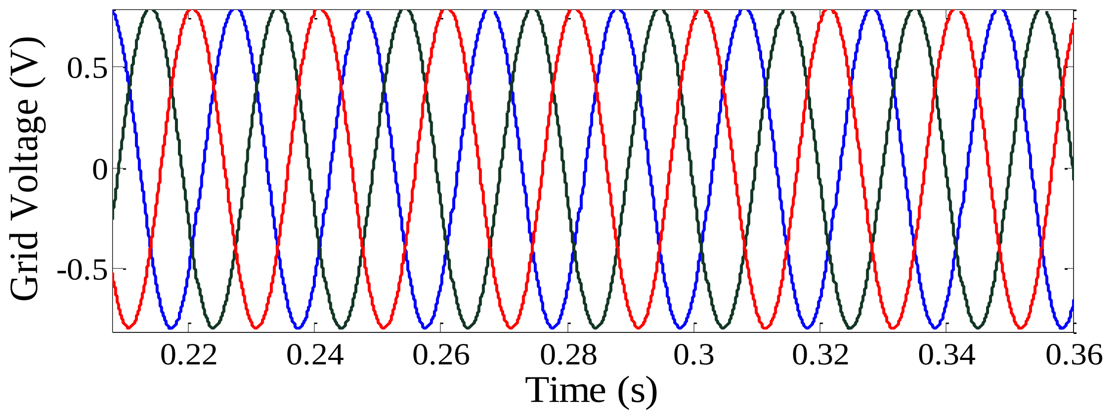


Figure 4.6: Three phase Grid Voltage

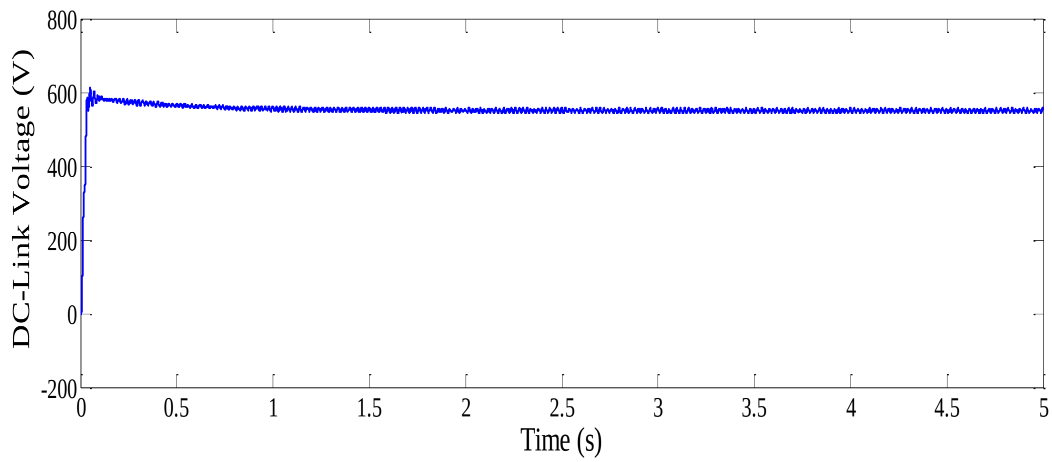


Figure 4.7: DC link voltage using PI Controller

4.6 CHAPTER SUMMARY

A sinusoidal three phase grid voltage is generated and fed to the PWM, so that pulses are generated and then the pulses are finally fed to the converter. Function of the converter is to maintain the dc link voltage constant at 550 V. The dc capacitor voltage is maintained constant with the help of PI controllers only. However the system suffers from variations as it is difficult to tune the PI controllers. The dc link voltage is maintained constant so as to maintain the value of frequency and voltage at rated value.

CHAPTER 5

IMPLEMENTATION WITH FUZZY PI CONTROLLER

5.1 OBJECTIVE OF THE CHAPTER

To design a fuzzy controller, to improve the performance of the dc capacitor voltage variation as compared to the performance of the traditional PI controllers. Design of fuzzy rules and different membership functions for the input and output DC link voltage control. Comparison of the performance regarding the use of simple PI output with the fuzzy PI output.

5.2 DESIGN OF A FUZZY CONTROLLER

The PI controllers always have a very vital role concerning the constancy of the power system. However the performance of the double fed induction generator greatly depends on the suitable choice of the control gain parameters of the PI. The difficulty regarding the PI controller gain is the fine tuning of the controller so as to achieve the optimal operation of the task. The major drawback of the PI controller is faced when the process is nonlinear and also when the system is having oscillations. Considering all these facts, a fuzzy logic controller was implemented. As fuzzy controller can work in linear as well as in nonlinear design parameters.

The advantage regarding fuzzy controller is the systematic approach to control a non linear based procedure depending on the knowledge and experience based of human being. A fuzzy controller can use multiple inputs and multiple output variables. The operation of fuzzy controller:

5.2.1 Fuzzification:

The term fuzzification means to fuzzify the data. This is done by converting the classical set to fuzzy set. For this process we need different fuzzifiers such as Triangular, Trapezoidal, Singleton and Gaussian. With the help of these fuzzifiers we assign some membership function to each and every input and convert it into fuzzy set.

5.2.2 **Membership function:** It is a graph between input and the membership value, which varies from 0 to 1. The membership function provides impreciseness to the fuzzy logic. There are various types of membership functions:

i. Trapezoidal
ii. Triangular
iii. Gaussian
iv. Sigmoid
v. Piecewise linear

5.2.3 Fuzzy Inference Engine:

It consists of knowledge base, in which the rules are framed. Fuzzy inference engine can be broadly categorized into two types of methods:

i. Mamdani method
ii. Sugeno method

Mamdani method is a fuzzy inferencing method in which the linguistic logic is used to make the rules. Mamdani method is easy to implement, user friendly and widely accepted method of fuzzy inferencing. The reason being is its wide area of application to most of the problems.

On the other hand sugeno method is based on mathematical analysis and calculations. It is more complex compared to the Mamdani method. Sugeno method works well with the linear systems. One major advantage is that it is computationally efficient.

5.2.4 **Deffuzification:** It is a process of converting a fuzzy set into classical set. It is the inverse process of fuzzification. It is of much importance as by deffuzification process we convert the fuzzy values back into the classical or crisp values. There are different methods for deffuzification such as the centroid method, bisector method, largest of maximum, middle of maximum and finally the smallest of maximum. Among all of this the most efficiently used defuzzification method is the centroid method. A fuzzy controller can operate in a broad range of operations along with the variation of the parameters and load existence as compared to PI controllers. Depending on the control requirements and operational conditions of the DFIG, a fuzzy PI control strategy is designed. Input to the fuzzy PI controller is the error, which is

continuously tracked and automatically corrected by the K_c and K_t controllers so as to achieve a dynamic performance.

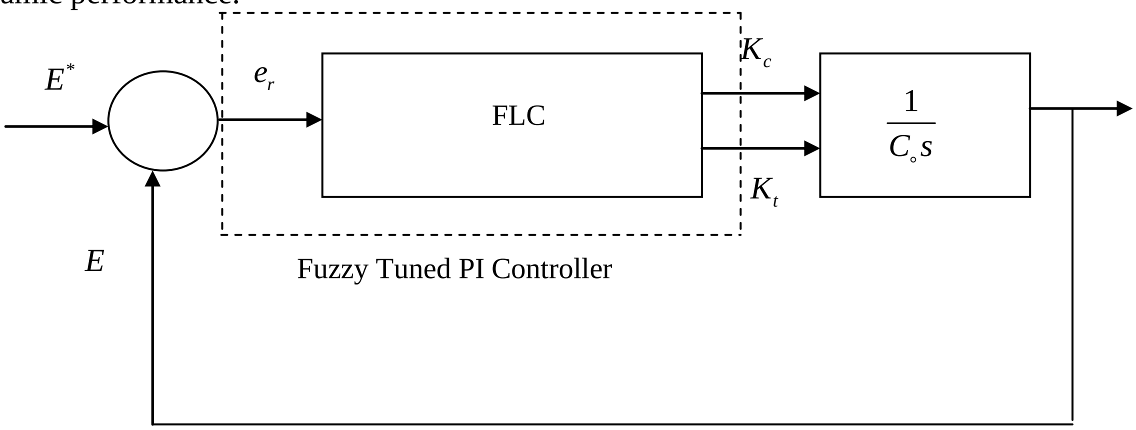


Figure 5.1: Block diagram of Fuzzy Tuned PI controller

K_c = Proportional Gain, K_t = Integral Gain

The input signal consists of nine membership functions and the two output's each consisting of five membership functions.

5.3 THE RULE BASE OF FUZZY CONTROLLERS

Table 5.1: Rule Base

e	K_c	K_t
NVH (Negative Very High)	VH (Very High)	VL (Very Low)
NH (Negative High)	H (High)	L (Low)
NL (Negative Low)	N (Normal)	N (Normal)
NVL (Negative Very Low)	L (Low)	H (High)
N (Normal)	VL (Very Low)	VH (Very High)
PVL (Positive Very Low)	L (Low)	H (High)
PL (Positive Low)	N (Normal)	N (Normal)
PH (Positive High)	H (High)	L (Low)
PVH (Positive Very High)	VH (Very High)	VL (Very Low)

Input Parameters for DC Link Voltage Control

Table 5.2: Input parameters for Error

Name	Type	Range
Negative Very High	Trapezoidal	[-5 -3 -1 -0.8]
Negative High	Triangular	[-1 -0.75 -0.5]
Negative Low	Triangular	[-0.8 -0.5 -0.2]
Negative Very Low	Triangular	[-0.5 -0.15 0.2]
Normal	Triangular	[-0.5 0 0.5]
Positive Very Low	Triangular	[-0.2 0.15 0.5]
Positive Low	Triangular	[0.2 0.5 0.8]
Positive High	Triangular	[0.5 0.75 1]
Positive Very High	Trapezoidal	[0.8 1 3 5]

Output Parameters for DC Link Voltage Control

Table 5.3: Output parameters for Proportional Controller (K_c)

Name	Type	Range
Very Low	Trapezoidal	[-2 -1 0 0.3]
Low	Triangular	[0 0.3 1.2]
Normal	Triangular	[0.6 0.8 1]
High	Triangular	[0.3 1.2 1.6]
Very High	Trapezoidal	[1.2 1.6 2 3]

Table 5.4: Output parameters for Integral Controller (K_t)

Name	Type	Range
Very Low	Triangular	[-4 -2 0 0.5]
Low	Triangular	[0 0.5 3.5]
Normal	Triangular	[1.5 2 2.5]
High	Triangular	[0.5 3.5 4]
Very High	Triangular	[3.5 4 6 8]

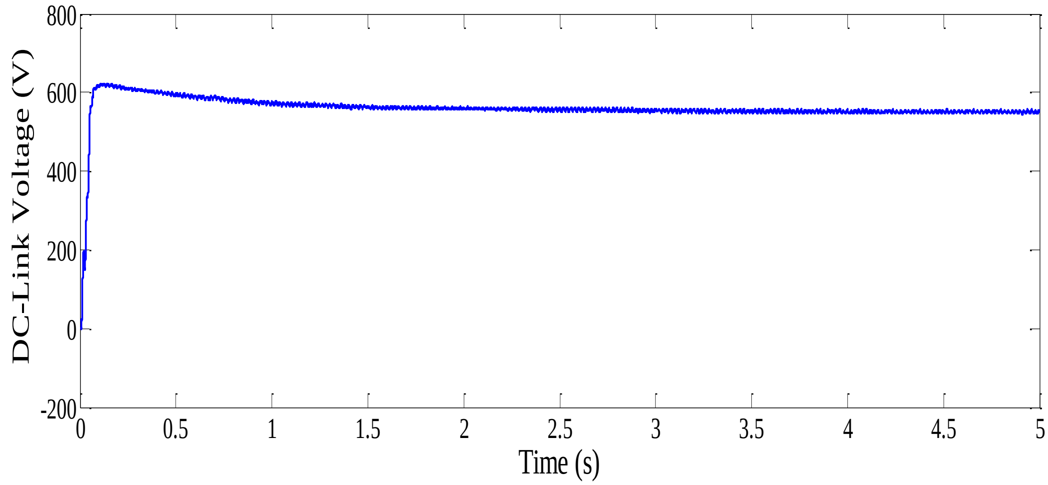


Figure 5.2: DC link voltage using Fuzzy PI Controller

The dc link voltage variation has been improved using fuzzy PI controller.

5.4 RESULTS

Comparison of the dynamic response behavior between fuzzy PI and traditional PI controller of double fed induction generator

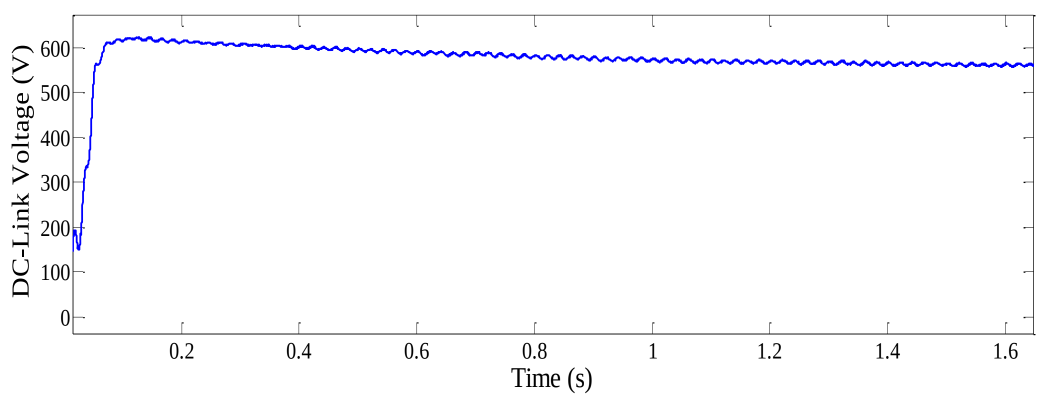


Figure 5.3: Dynamic response of the system using Fuzzy PI Controller

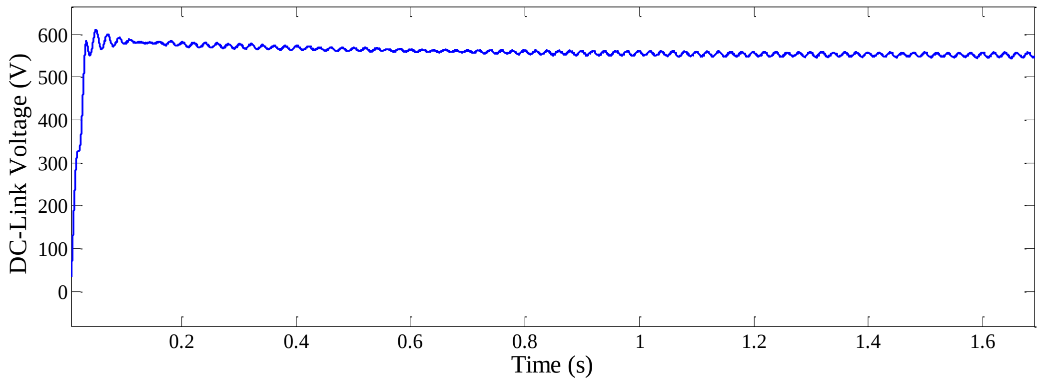


Figure 5.4: Dynamic response of the system using PI controller

Percentage Overshoot	Remark
PI	14%
Fuzzy PI	9%

5.5 CHAPTER SUMMARY

The characteristic plot of Fig 5.2 is obtained by simulating the supply side converter with the help of fuzzy PI controllers. With the use of fuzzy PI controllers the fluctuations in the curve are greatly reduced. Therefore a faster and dynamic response is achieved with almost no overshoot and faster settling time. By comparing both the results regarding the control of DC link voltage variation, an observation is made, proving that the response of the system can be greatly improved by more precised use of fuzzy PI controllers.

CHAPTER 6

CONCLUSIONS AND SCOPE OF FUTURE WORK

6.1 CONCLUSIONS

Modeling of the wind turbine is done so as to control the amount of power extracted from the wind. From the Fig 2.5 we have seen that with the increase in the velocity of the wind, the capacity to extract power also increases. However, if the velocity of wind will keep on increasing, the output power will also increase and if the wind speed continues to rise further a control system will be required to limit the output power. This is done by modeling of the turbine blades to ensure a safe operating region for a wind turbine. A DFIG is used instead of synchronous generator due to its nature of variable speed and improved amount of power quality and also it reduces the cost of the converter used. The modeling of the Double fed induction generator is done from the abc variables to the dq axis variables, so as to reduce the number of variables and also to reduce the complexity of the model.

Proportional integral controller action

The Fig (3.4, 3.5) shows the equivalent circuit diagram for the separate d and q axis. A thorough review is done relating to modeling and control of the grid side using vector control strategy. The vector control strategy that is implemented for the grid side control ensures a decoupling strategy of the stator side. A simulation model is represented in Fig 4.1 proving that the dc link voltage is maintained constant using a PI controller. A PLL control technique block was used to measure the phase angle. In the traditional PI control, two loops namely current control and voltage control loop have been implemented.

Fuzzy PI controller action

However, a new improved and a convenient strategy, fuzzy PI technique has been further developed to control the dc link voltage. In the case of fuzzy PI control, error has been taken as the input value and the output showing different K_c and K_t values has been listed in the table. Different K_c and K_t for the current control and voltage control loop have been noted. A comparison plot has been done between the simple use of PI and fuzzy PI, to ensure the best among the controller. The result showed the fuzzy controller was superior in performance as compared to the traditional PI controller.

6.2 SCOPE OF FUTURE WORK

I. To implement fuzzy PI concept in the machine side converter to achieve better performance results.

II. Extraction of the maximum power from the wind using MPPT algorithm.

III. Try to simulate the fuzzy PI controller using improved membership function and rules to obtain a better stability of the dc link voltage.

APPENDIX – I

Parameters of wind turbine

Radius =35 m

Pitch angle = 0

(i) Cut in speed = 4 m/s; Maximum speed = 12 m/s

(ii) Cut in speed = 12 m/s; Maximum speed = 22 m/s

Sources

Three phase 250 V, 50 Hz

Line resistance= 0.1 Ω

Line inductance= 12 mH

Current control converter

Sampling time=0.5 ms

DC link control converter

Sampling time= 5 ms

Reference Dc link voltage = 550V

Capacitor= 2.4 mF

Load

Load resistance = 40.33

Power = 7.5 KW

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